Early Experiments at the Arecibo Observatory---Cross Modulation for Measuring D-Region Electron Densities Generation of ELF/VLF Signals by Modulating the Dynamo Current System

Presented at the 50th year anniversary of the Arecibo Observatory

Presented by A. J. Ferraro, The Pennsylvania State University

Abstract

This paper briefly summarizes the research that the Penn State University team has accomplished using the heating facilities of the Arecibo Observatory. Heating experiments covered two broad areas. One using the cross modulation experiment (also known as the Luxembourg effect) to measure D-region electron densities . Originally done at the PSU heating facility and then moved to the Arecibo facilities. The other area was involved in modulation the dynamo current system in order to generate ELF/VLF signals useful for submarine communications.

The former data was used to support in the understanding of the physics and chemistry for the formation of the D-region. Earlier results at Arecibo attempted to compare those results with the incoherent scatter measurements of low-lying ionization.

The generation and measurements of the ELF/VLF signals were made at close, then moderate then much longer paths. These will be discussed.

An important part of our program was in the design of the final heating antenna at Islote. The author, Breakall and LaLonde were instrumental with this design. Prior to that antenna, a HF log periodic antenna was placed above the dish and measurements proceeded for a few years in that mode until the completion of the Islote antenna array. Due to a loss of the Islote array in a hurricane, HF heating was at a standstill but a new antenna design by Breakall will again place an improved array above the dish to allow future heating experiments. The modulation of the dynamo current system led to conducting the experiment using other current systems like the equatorial electrojet and the polar electrojet. Arecibo provided a rich environment for the PSU researchers to continue their efforts. We thank Arecibo for the great support from all that was given to us.

Introduction

This paper briefly summarizes the research that the Penn State University team has accomplished using the heating facilities of the Arecibo Observatory.

Heating experiments covered two broad areas. One area used the cross modulation experiment (also known as the Luxembourg effect) to measure D-region electron densities. Originally done at the PSU

heating facility and then moved to the Arecibo facilities. The other area was involved in modulation the dynamo current system in order to generate ELF/VLF signals useful for submarine communications. The former data was used to support in the understanding of the physics and chemistry for the formation of the D-region. Earlier results by John Matthews at Arecibo attempted to compare those results with the incoherent scatter measurements of low-lying ionization.

Described briefly is the PSU program to gain insight of how activities were initiated at the Arecibo Observatory. In the earlier 60s limited means were available for collecting large quantities of D-region data under a host of various geophysical conditions. This led the author to review carefully ground-based methods and improvements to the experiments. The wave interaction technique (also know as the Luxembourg effect) was just beginning to be used by Fejer1 . This effect relies upon a higher power radio signal (disturbing wave) to modulate the imaginary part of the index of refraction, hence affect the absorption of a probe wave (called the wanted wave). The measured periodic amplitude modulation upon the probe wave can be used to deduce the electron density in the D-region (with lots of mathematical difficulty). The change incorporated by the author was to also look at the phase of the probe wave since the real part of the index of refraction would also be affected by the disturbing wave. The idea was that measuring both the amplitude and phase affects would double the amount of data and lead to better results. PSU pursued this concept and installed the first heating facility on the western hemisphere. See figure2 for the interplay of the wanted and disturbing signals.

Figures 4, 5 and 6 show the receiving unit, the 500 KW pulsed disturbing signal emitting 4.5 MHz and the antenna array. ERP was on 11 MW, small by today's standards but one did not want to cause excessive disturbance to the ionosphere since the ambient ionization was desired. Figure 7 shows what happens when one operates on 4.5 MHZ which easily propagates. FCC shuts down the facility. Arecibo had a facility in operation so fortunately we found a home after several discussions with the director Dr. Tor Hagfors. Above is the long story how we became frequent visitors to the Observatory.

Early Wave Interaction Operations at Arecibo

Figure 8 pictorially depicts a log periodic hanging above the dish to serve as a heater antenna. Figure 9 is a shot of the actual log periodic which suffered from corona at the ends of some of the elements. This made operations difficult.

At Los Canos was housed, Figure 10, the wave interaction processing equipment (CM) along side of the ELF receiving equipment to be described later. However Mike Sulzer, Figure 11, designed improved equipment while working on his graduate studies. Mike took us from the

vacuum tube era into the solid-state era. It was a suburb piece of engineering. Figure 12 shows the homemade wanted, or probing transmitter, which was also housed in the building at Los Canos.

Data taking continued for some time but soon sponsors thought satellites would replace the need to employee HF prediction methods and knowledge of the ionosphere would lose its popularity and funding. At this juncture our research direction changes course (Figure 13 says it all).

How many remember the Sexy Nightclub down the road at Los Canos?

The ELF/VLF Generation Program at Arecibo

Our sponsor requests looking for alternate ways to generate and radiate ELF/VLF signals ultimately for submarine communications. The method that has been employed was a ground based ELF transmitting facility at the Michigan and Wisconsin sites. 73 Hz was the frequency in use; long wire antennas, 22 miles long, were used but they were still a faction of a wavelength at 73 Hz. Never the less the waveguide attenuation at his frequency was so low that the signal could be propagated globally. The skin depth effect was moderately large so the signal could reach submarines at their maximum depths. Although an ideal approach, there was great resentment by the public who equated this operation with subs carrying nuclear weapons. The resentment grew into attacks upon the facility involving sawing down antenna support poles and other destructive activities. Because of this the Government closed the facility. Now the time was ripe to propose alternate methods.

The PSU team looked into generating ELF/VLF by using the natural current system in the ionosphere as a potential radiator. At Arecibo the dynamo current is the prevalent current system in the lower part of the ionosphere. Figure 14 shows the proposed technique. A high power HF transmitter emits pulsed signals at the pulse rate of a desired ELF signal, let us say 1000 Hz. The HF source causes increased absorption through which the dynamo current is passing. In simple terms, the resistance of that region is increased and the current density diminished and some of the current density can travel the path around the heated volume.

At any point inside or out of the heated volume the current is changed and when the heater is pulsed off all returns to ambient conditions with some time constant. In any event the current density at these points will be increasing and decreasing at the pulse repetition rate of 1000 Hz.

Thanks to Maxwell the heated region and surrounding region must radiate. Thus a 1000 Hz signal and its harmonics radiate into the earth ionosphere waveguide and propagated there in.

Figure 15 shows a map of the dynamo current, with 10,000 amperes between the lines. Current densities diminish at night and are stronger by day as one can deduced from the Figure. Figure 16 summarizes the simple picture of generating a time varying signal from a modulated dynamo current system.

The Islote Heating Antenna array

The heater array at Islote was used in the ELF/VLF generation research program (Figure 17). The array got its start from initial meetings between Breakall, LaLonde and the author. Several designs were considered but the one finally chosen was an array of inverted log periodic dipole

elements. Figure 18 is a partial view of the maze of wires. That is Breakall in the picture. Figure 19 shows the younger Breakall! Little did he realize at that time that he would become one of the best antenna designers known in the community and an asset to the Observatory. Figures 20 and 21 are further views of the structure. Aiding in managing the erection of the array was Al Veldise, a retired antenna engineer

from AEL corporation and a new graduate student from PSU, Chris Trask. Figure 22 is the remains of the array after a hurricane. I believe the towers are no longer there. Breakall will describe his newest heater antenna.

Measurements of ELF/VLF over Several Paths

A lot of data was taken under local conditions, i.e., the ELF/VLF receiving equipment at Los Canos was nearby the heating source at Islote. It was clear that the method worked and data could be reproduced. The ELF/VLF signal was present during the daytime, disappeared at night since the dynamo current was weaker at night and there was less D, E region absorption to make the depth of modulation strong. It was now time to reach out further.

We had hoped to have shipboard measurements by spinning around the Island trying to estimate the pattern of the radiation but our sponsors suggested a cruise ship. Cruise ships don't take you were you wish to go unless for a vacation! We had a complex full wave model of the fields expected in the earth ionosphere waveguide due to an imbedded dipole in the ionosphere, Carroll2 et al. Figure 24 shows a path for which 2 weeks of measurements were successfully accomplished. Figure 25 shows Tom Collins making the shipboard measurements using a ELF/VLF loop antenna.

Next we tried a very long path; Islote to the field site, Scotia, at the PSU receiving site for a distance of 1675 miles. The signal to be generated was a simple binary message, 1011. The heater transmitters were modulated with a sine wave instead of a pulse. By shifting the modulating signal 180 degrees and back to zero degrees we could create the binary quantities "1" or "0". Correlation measurements clearly showed the four bits were received correctly. However some in the scientific community thought this could not be true. We conducted several tests to convince ourselves that it was a real effect. It gave me thought of Alexander von Humboldt's statement, shown on Figure 28. The event is denied as true, then denied it is important, finally they credit the wrong person. Many of you might have had this feeling about your scientific endeavors.

Achievements at other Heating Facilities

A brief description of research at other heating facilities follows.

The ONR provides funding, Figure 29, to examine ELF/VLF generation with a polar electrojet (PEJ) and the equatorial electrojet (EEJ). HIPAS in Fairbanks, AK provided the first opportunity to evaluate generation with a PEJ. The PEJ can be very strong and provided higher field strengths of generation than from the dynamo current. However it is not predictable.

The HIPAS facility heater array was a set of 7 dipoles, six equally positioned on a circle and one in the center. Transmitters fed each dipole. One could phase the elements to create different HF patterns. One in particular was a double main beam with about 20 degrees between centers of the beams. Thus creating a two element ELF/VLF antenna from the modulation of the current system. Further by shifting the phases of the elements to its neighboring elements causes a rotation of the two heated regions because of the circular symmetry of the heater array. Thus one can step the locations of the two heater

beams around a circle. As to be expected the direction of the generated signal could be made to point in different azimuthal directions. A mobile ELF/VLF receiver was positioned 290 miles from HIPAS as shown in Figure 30. One could correlate the strengths of the received signal with angular positions of the two element ELF/VLF array in the ionosphere. Since submarine communications was an objective, being able to direct t he signal seemed like an important point t consider. The HIPAS array did not permit more than two heated regions but future arrays could be designed to create a larger ELF/VLF array.

The EEJ was tested at Jicamarca, Peru even though the heating frequency was far from being optimized for heating but it did work. See Figure 31. Signals were weak but they were generated.

Finally HAARP was funded, Figure 32, a facility in AK. Penn state did not do any generation experiments there but Breakall, Collins and Ferraro played a role in the design, modeling, and testing of scale models. Figure 33 shows the final HF array with 12 by 15 elements.

Figure 34 shows the typical loop antennas used to receive the ELF/VLF signal, modest by comparison to heater arrays.

Figure 35 shows the ERP in dBw for various facilities.

This has been a brief overview of the work done at Arecibo and we wish to thank all staff that provided for the assistance to make our experiments successful.

Early Experiments at PSU, Arecibo, Jicamarca, HIPAS and HAARP

Cross modulation experiments to measure D-region Electron densities, first done at PSU then to Arecibo.

Later

ELF/VLF generation by modulating the current system

Presented at the 50th year anniversary of Arecibo
by A. J. Ferraro , Penn state University

Fig. 1

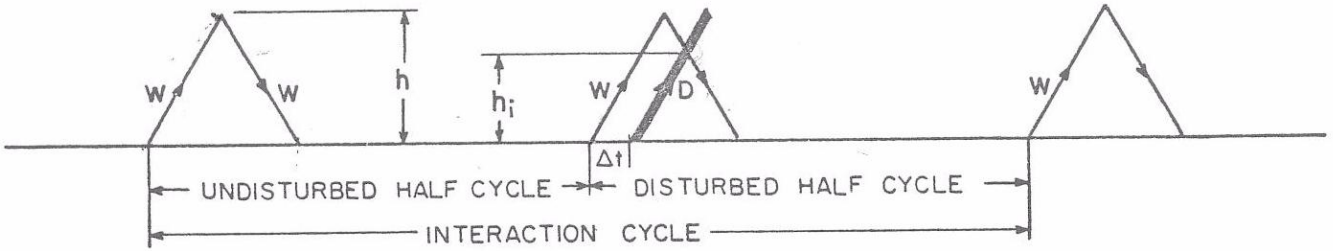
Penn States involvement with D-region heating began in 1963 with the pulsed cross-modulation experiment.

Our interest was with measuring the normal D-region electron densities and better understanding the physic of formation of the D-region.

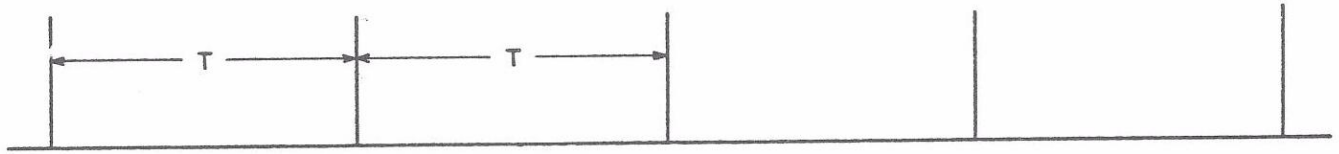
Later, 1980, we began ELF/VLF generation At AO

Fig 2

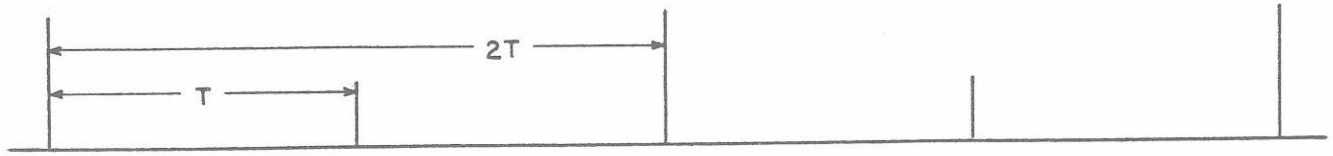
Elementary description of the wanted (W) and disturbing (D) waves interacting in the D-region of the ionosphere



a HEIGHT OF WANTED AND DISTURBING ENERGY PACKETS AS A FUNCTION OF TIME



b AMPLITUDE OF WANTED ECHOES AS A FUNCTION OF TIME IN THE ABSENCE OF INTERACTION



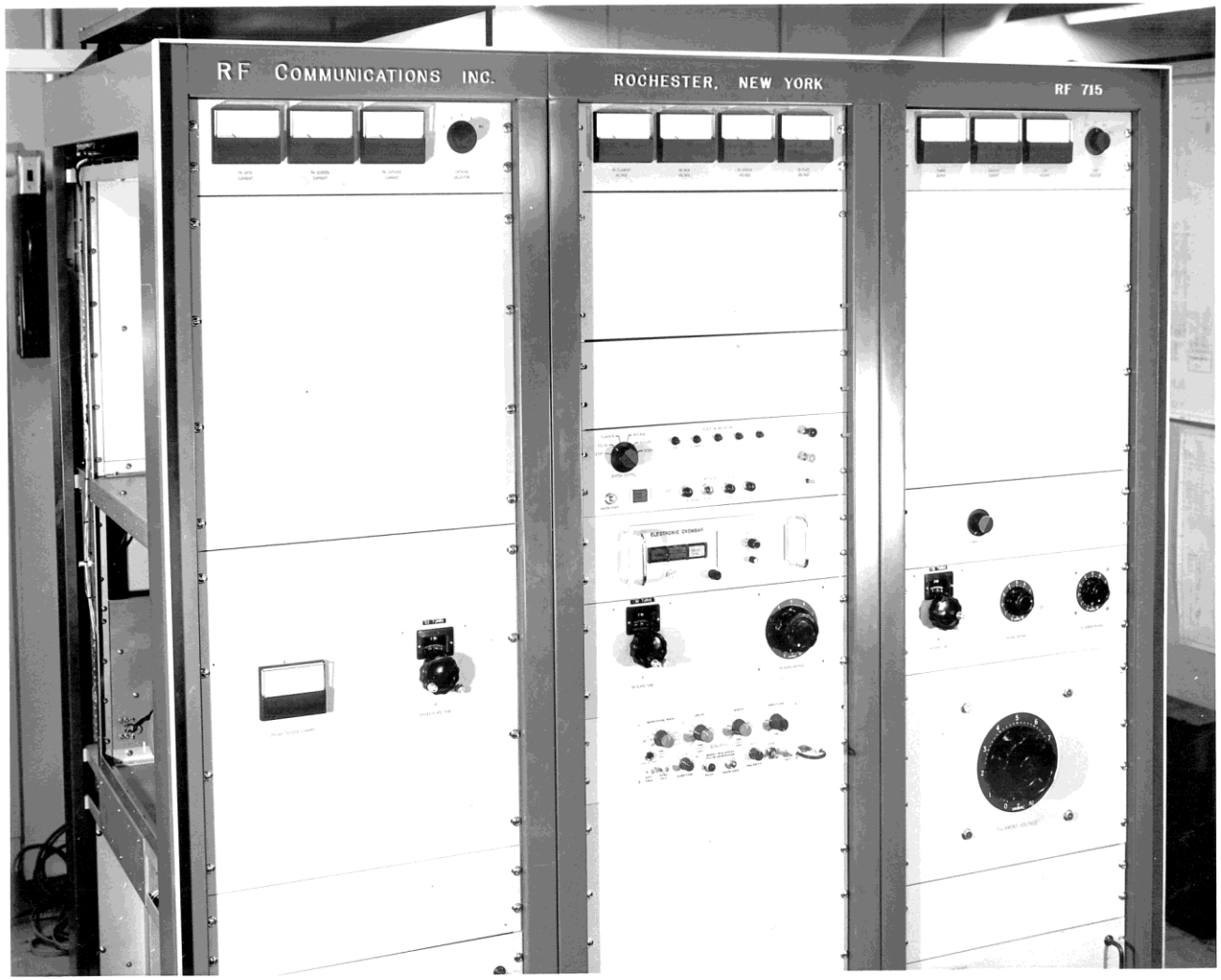
c AMPLITUDE OF WANTED ECHOES AS A FUNCTION OF TIME IN THE PRESENCE OF INTERACTION

GRAPHIC REPRESENTATION OF THE FEJER METHOD

Fig 3

THE PSU CROSS-MODULATION RECEIVING UNIT

Fig 4



THE 4.5 mc/s, DISTURBING 500 kw PULSE TRANSMITTER

Fig 5

PARTIAL VIEW OF THE 4.5 MHZ DISTURBING ARRAY AT SCOTIA NEAR PSU RESULTING IN 11 MW ERP

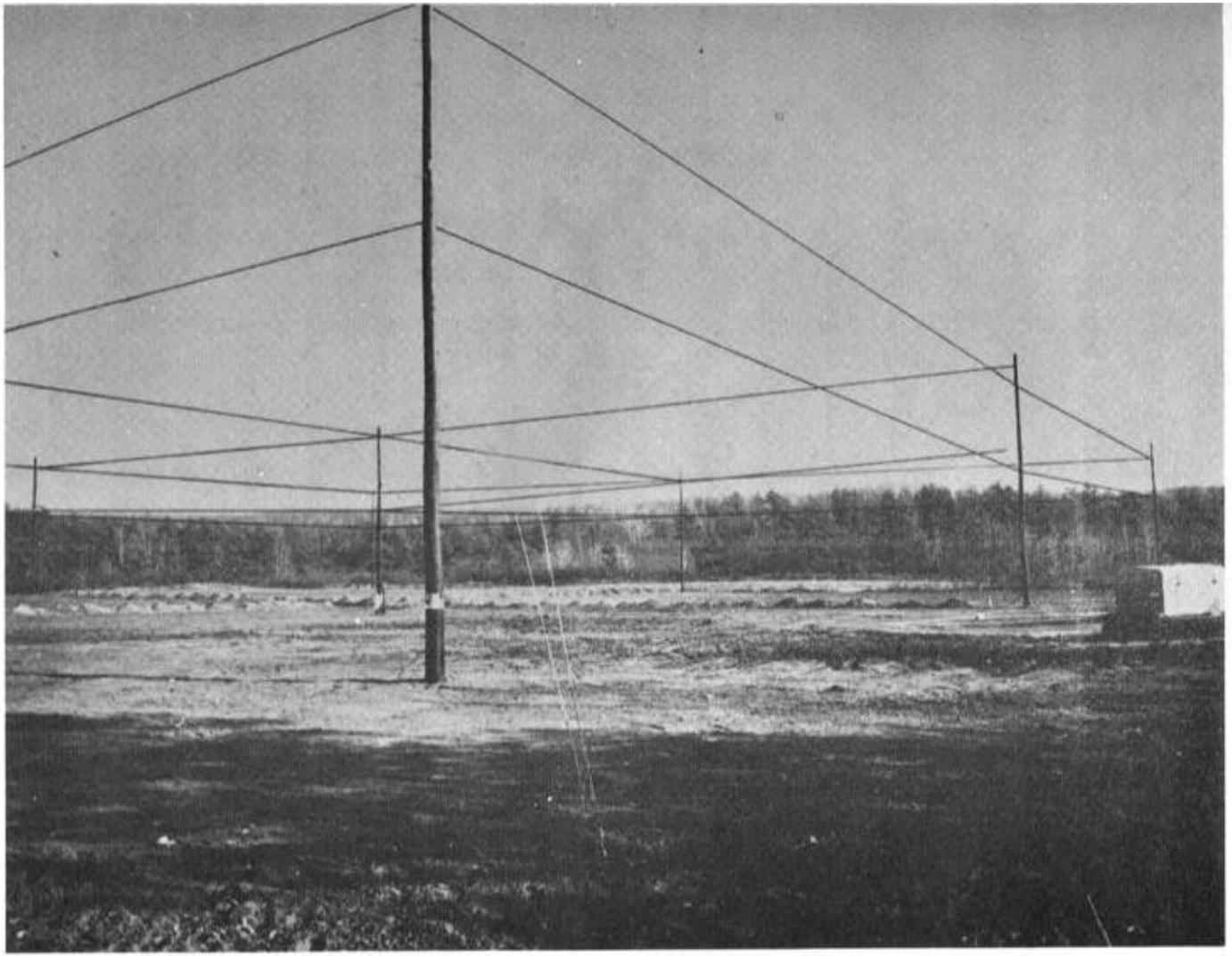


Fig 6

THE FCC SHUTS US DOWN, WE INTERFERRED WITH TOO MANY OTHER SERVICES.

WE MOVED TO ARECIBO , PUERTO RICO TO CONTINUE.

OUR RECEIVING EQUIPMENT IS REDESIGNED AND WE MAKE USE OF HEATERS AND ANTENNAS AT ARECIBO

Fig 7

THE FIRST HEATING EXPERIMENTS USED A HF LOG PERIODIC ARRAY SUSPENDED OVER THE DISH AS A GIGANTIC GROUND PLANE

Fig 8

THE FIRST HEATING EXPERIMENTS USED A HF LOG PERIODIC DIPOLE ARRAY

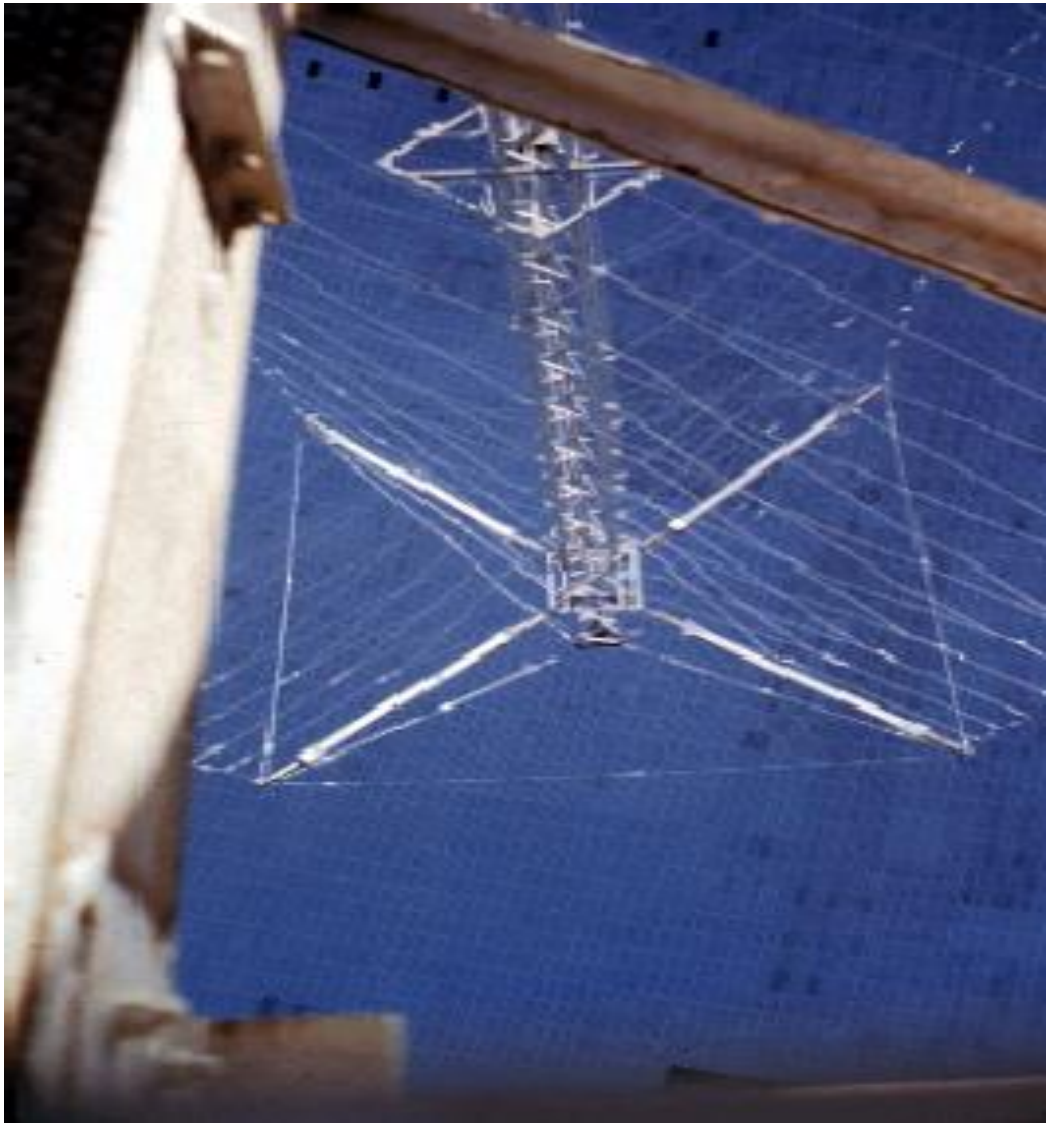
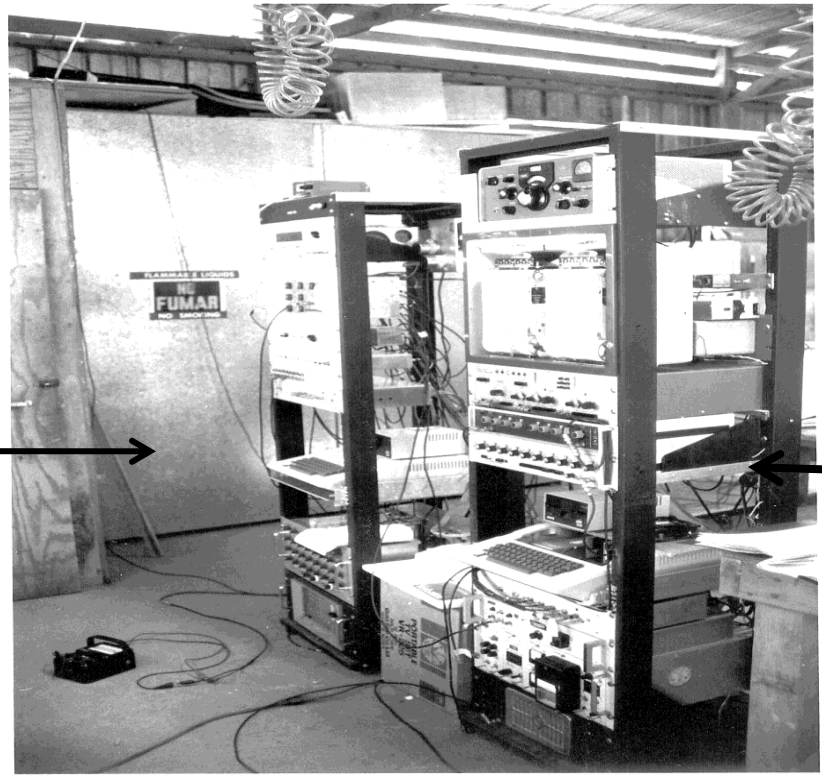


Fig 9

ELF/VLF receiving equipment at Los Canos, PR

CM



ELF

Equipment Installation at Los Canos
(Wave Interaction Rack Left, VLF/ELF
Rack on the Right)

1984

Fig 10

THE NEW IMPROVED CROSS MODULATATION SULZER RECEIVER AT PUERTO RICO

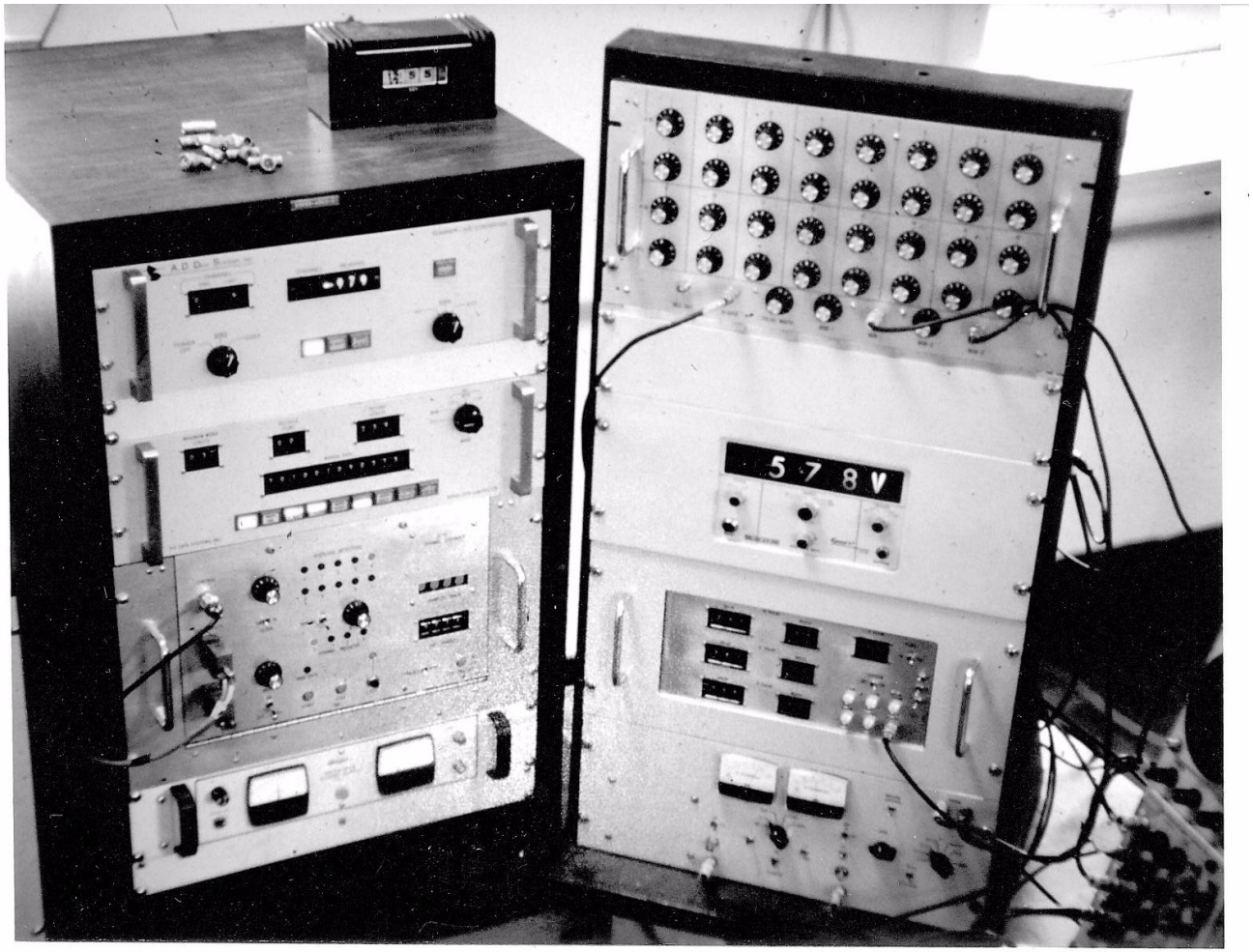


Fig 11

THE 2.5 MHZ , 2 KW, PULSED WANTED TRANSMITTER ARRIVES IN PUERTO RICO

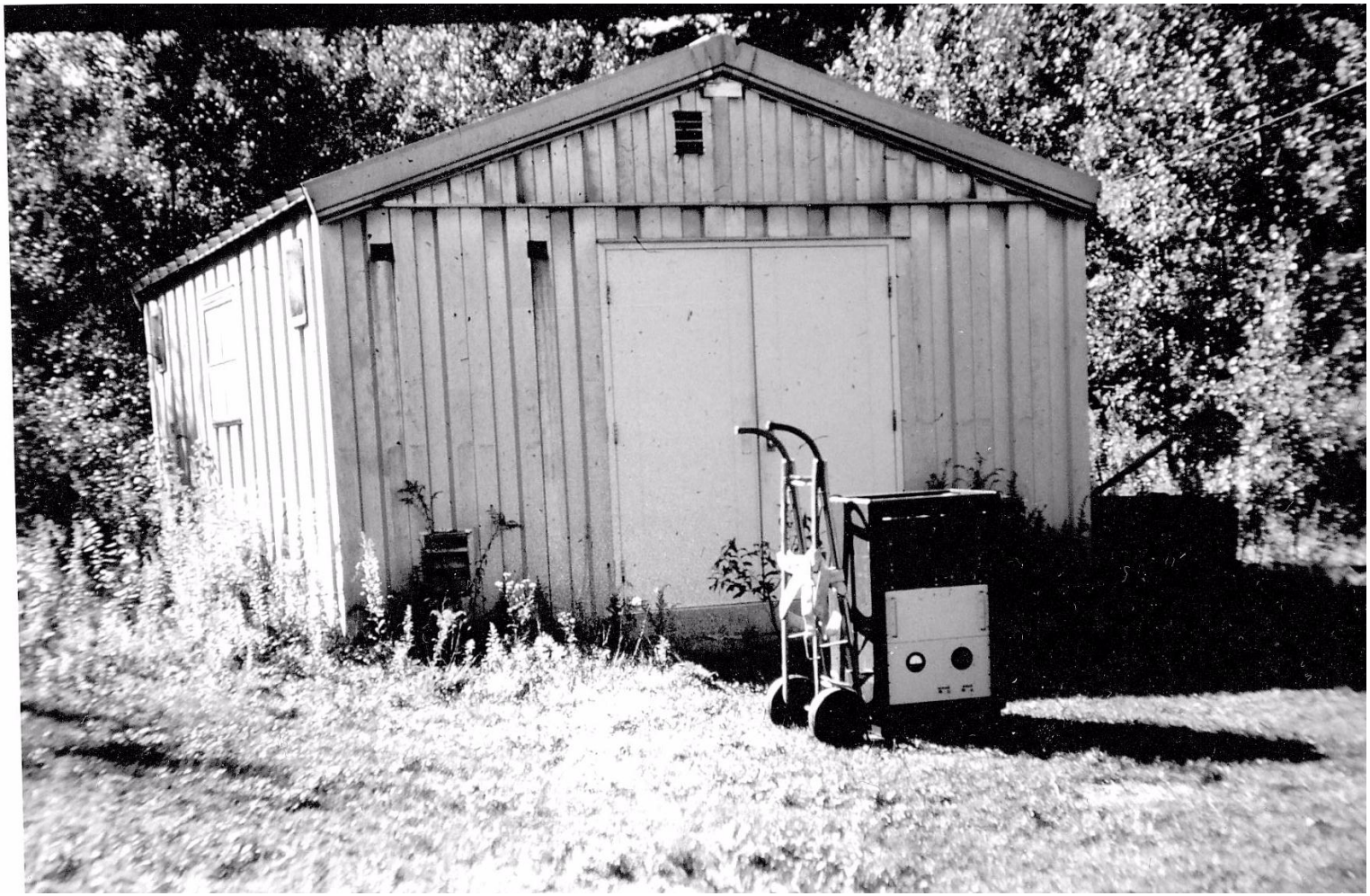


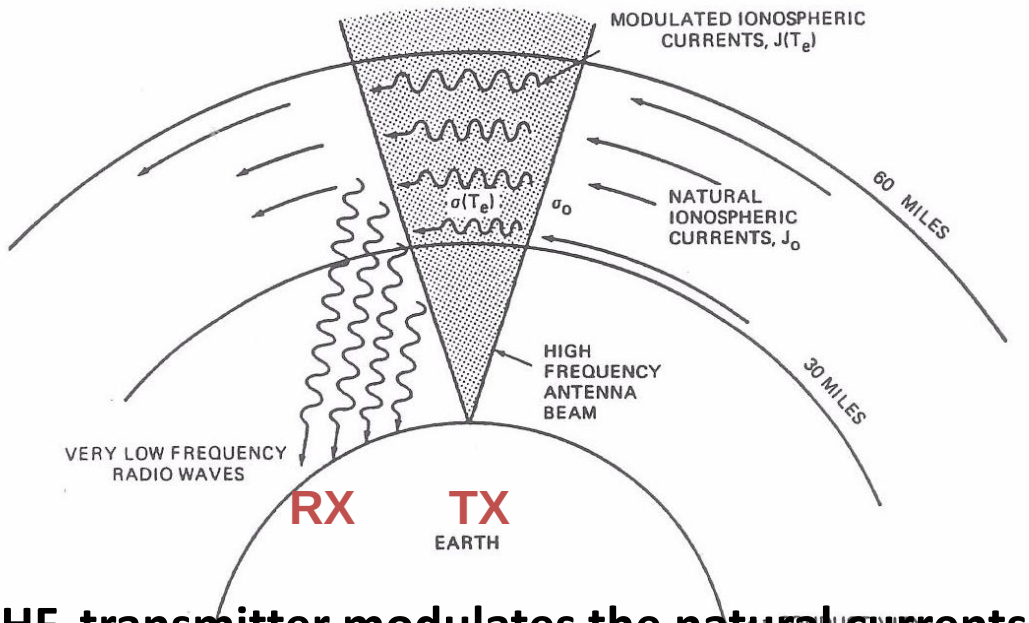
Fig 12

OUR RESEARCH DIRECTION TAKES A DIFFERENT COURSE. THE NAVY IS INTERESTED IN ALTERANTE METHODS TO GENERATE ELF/VLF FOR COMMUNICATIONS WITH SUBMARINES.

GROUND BASED SYSTEMS AT THE MICHIGAN/WISCONSIN ELF SITE ARE UNDER PUBLIC FIRE. A BACKUP METHOD IS DESIRED

Fig 13

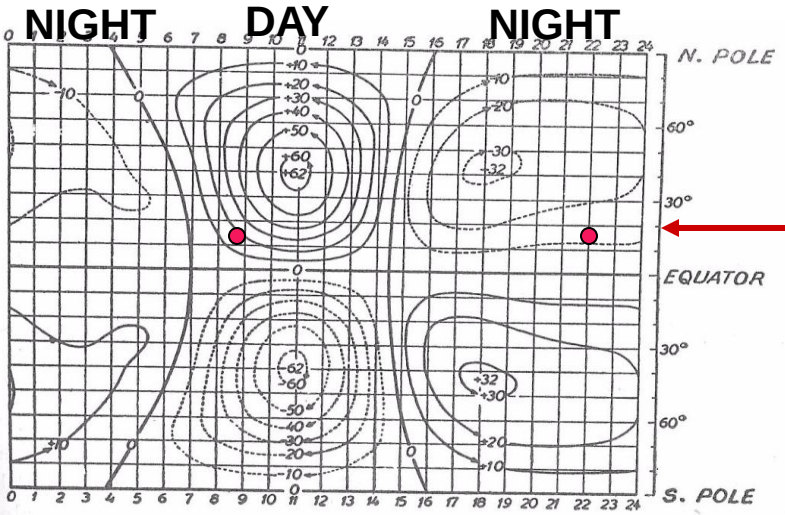
Heating the current system to generate ELF/VLF



A high power, HF, transmitter modulates the natural currents in the ionosphere and creates an antenna which radiates the same frequency as the pulse rate of the HF transmitter. The resistance of the ionosphere is modulated hence the current becomes modulated. Hence an antenna in the sky!

Fig 14

The ionosphere dynamo current due to solar and lunar tidal forces

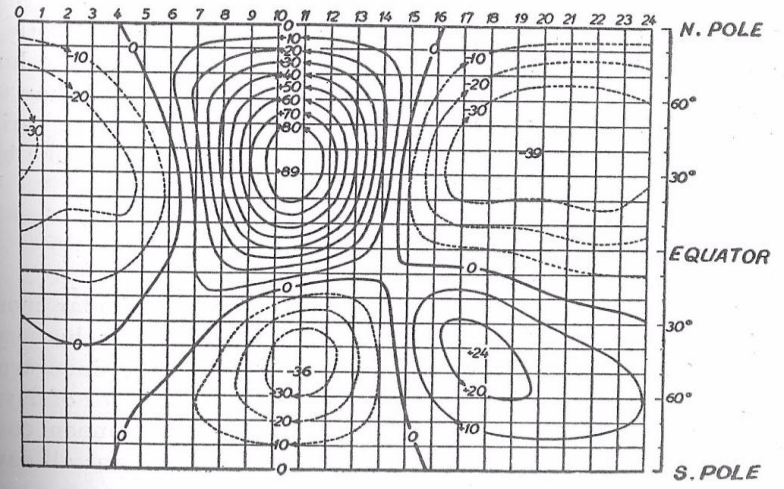


Arecibo

Equinox

FIG. 12. Upper atmospheric current system at a height of about 100 km. which may produce the observed S_q variation of magnetic elements during the equinoxes. (After Chapman and Bartels.)

10,000 amperes between lines

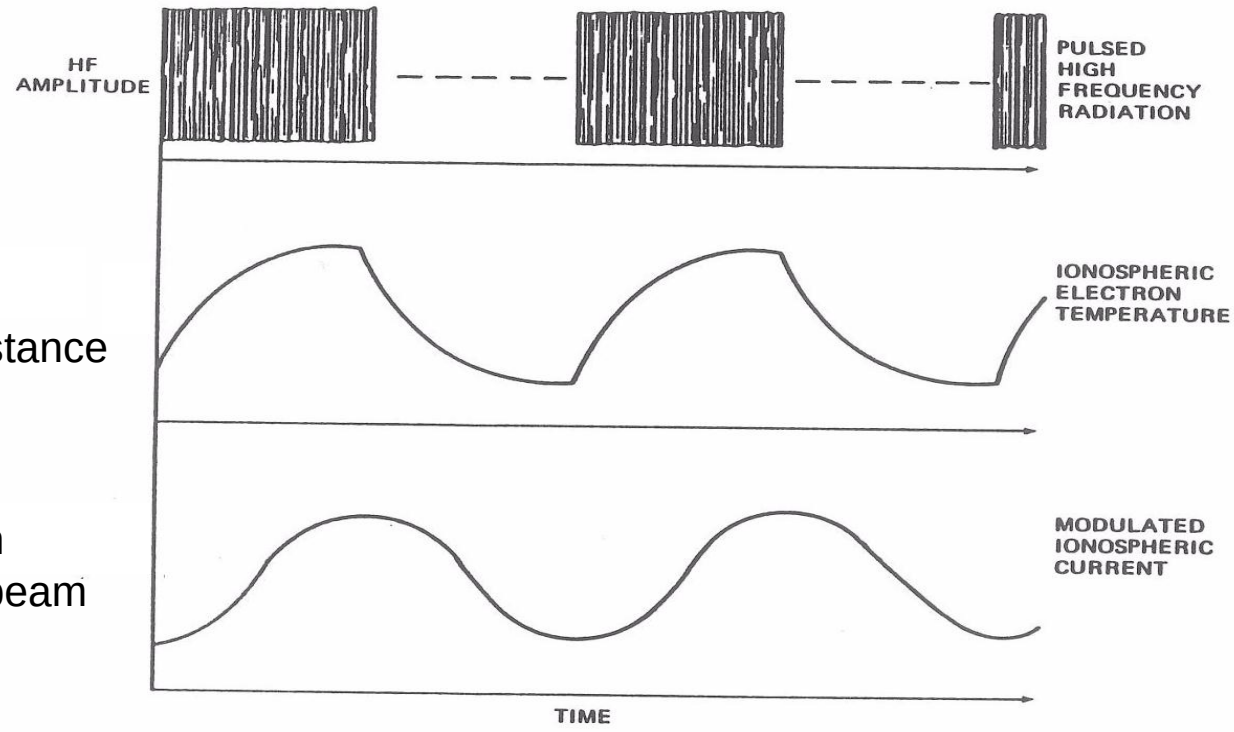


June

FIG. 13. Upper atmospheric current system at a height of about 100 km. which may produce the observed S_q variation of the magnetic elements in June. (After Chapman and Bartels.)

Fig 15

ELF/VLF modulation and the resultant ELF/VLF current



Resistance

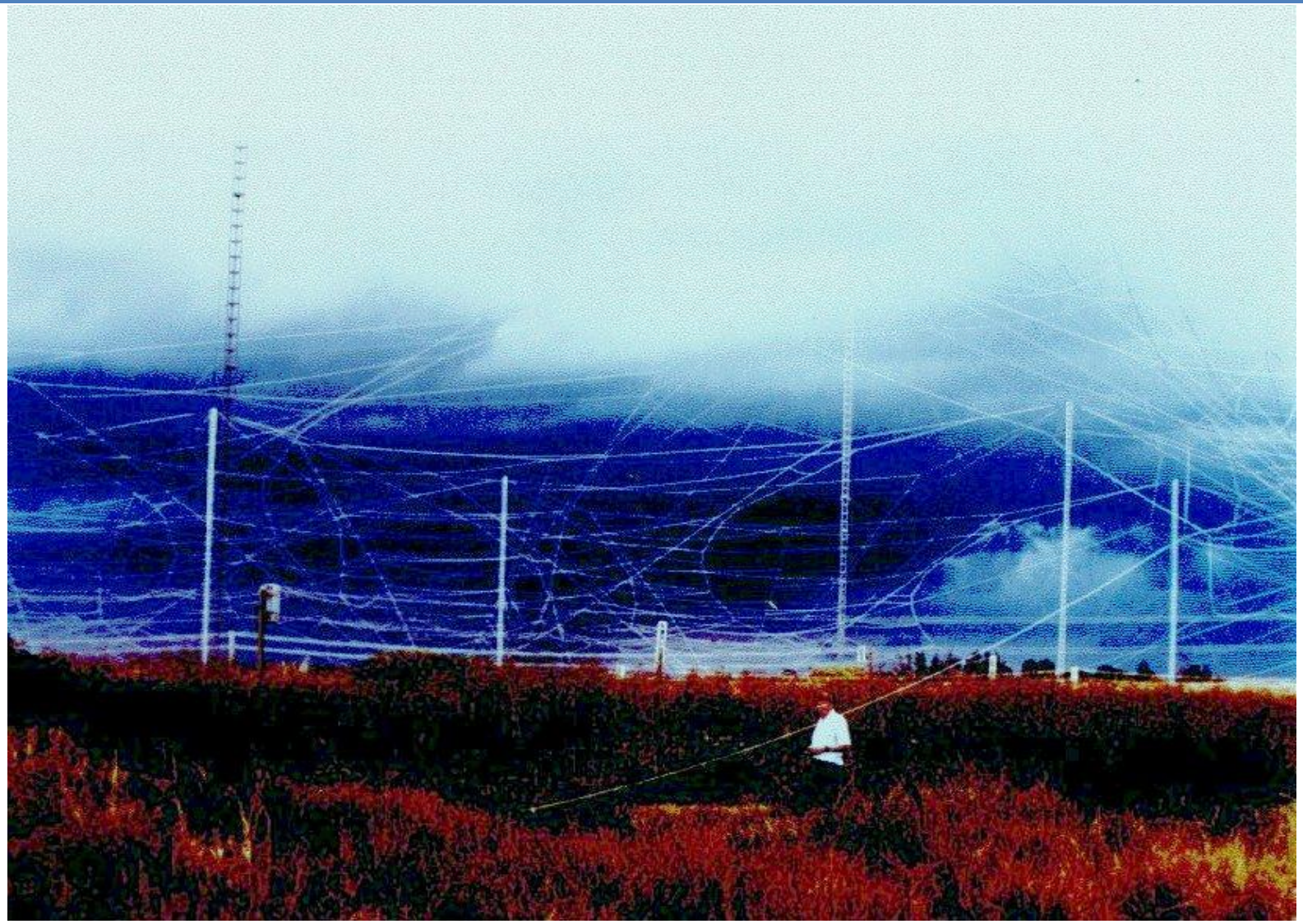
Current in
the mainbeam

Fig 16

A NEW HEATING FACILITY IS FUNDED AT THE ARECIBO OBSERVATORY.
THE RADIO ASTRONOMERS DON'T WANT TO PUT UP WITH THE IONOSPHERE TYPES PUTTING XMAS DECORATIONS ON THE DISH.

IRL DESIGNS THE ANTENNA ARRAY (Breakall, LaLonde and Ferraro)

Fig 17



Partial view of the antenna array designed by Breakall and Ferraro for heating experiments at the Arecibo Observatory

Fig 18

Fig 19

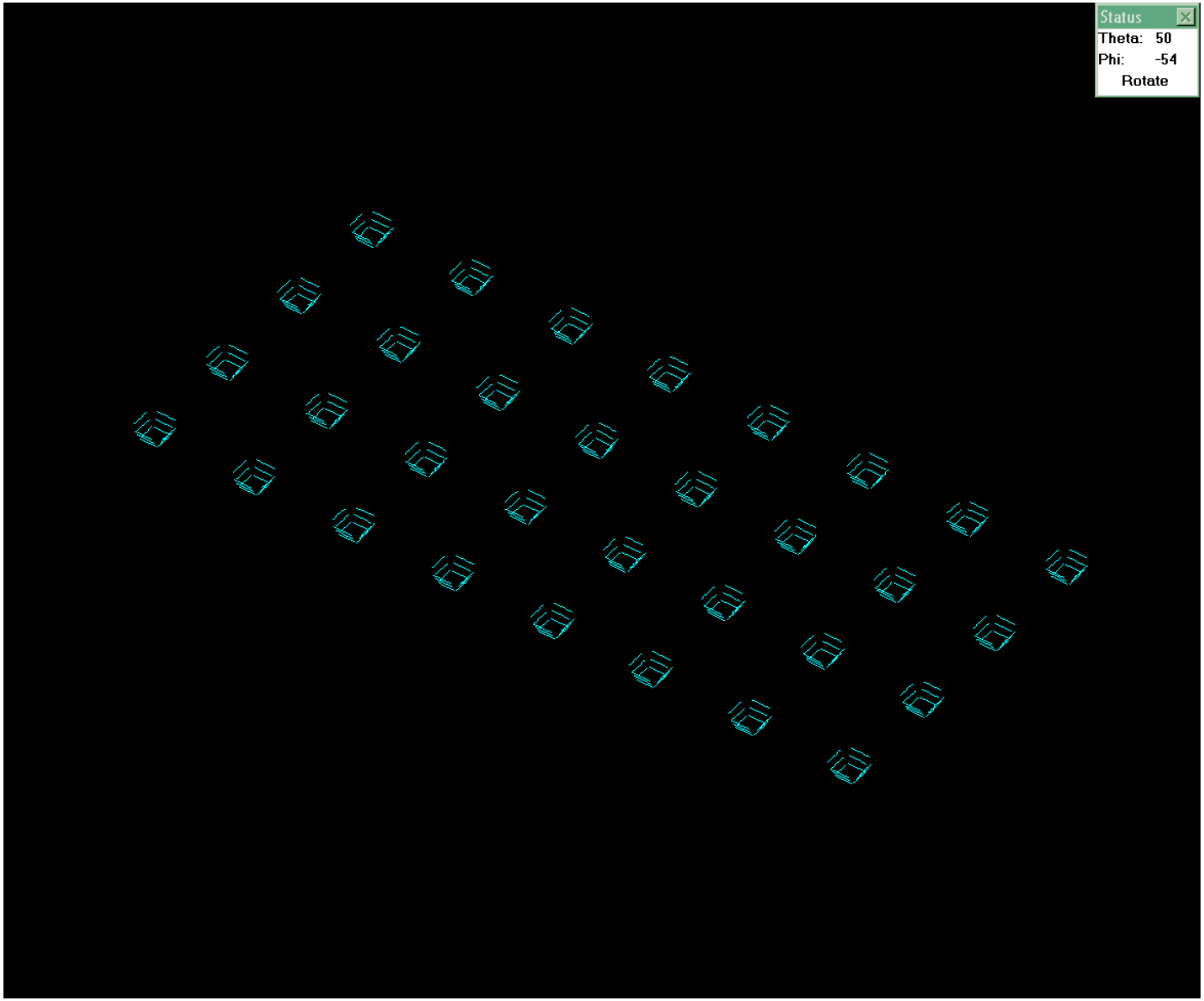


Fig 20

Artist's conception of the array

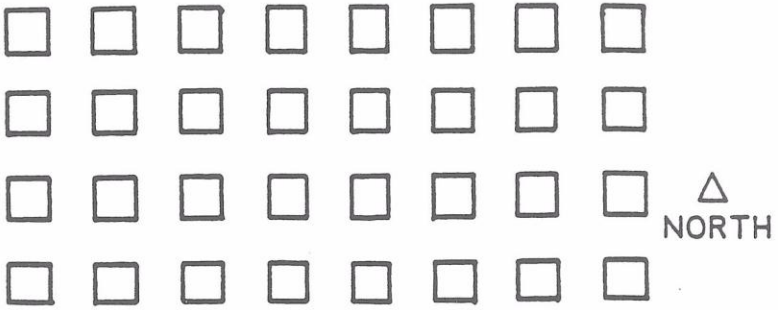


Figure 2.1 Arecibo Observatory HF heating array element arrangement.

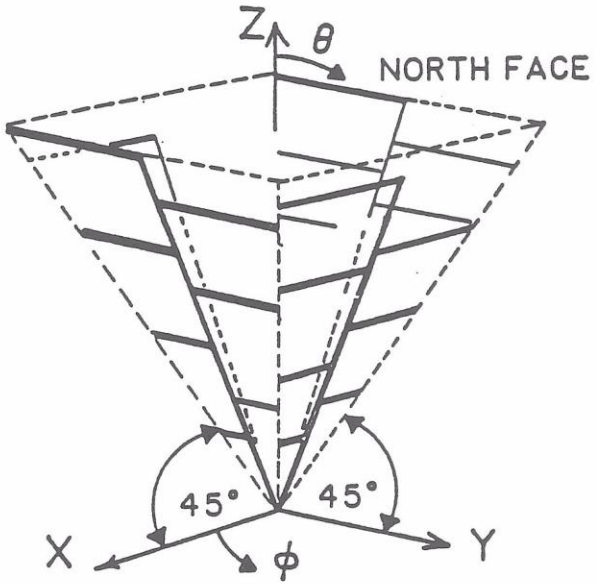


Figure 2.2 Arecibo Observatory HF heating array element structure.

Basic antenna array concept: 32 inverted LPDA.
Breakall, Ferraro, LaLonde, Veldise and Trask

Fig 21

After the hurricane

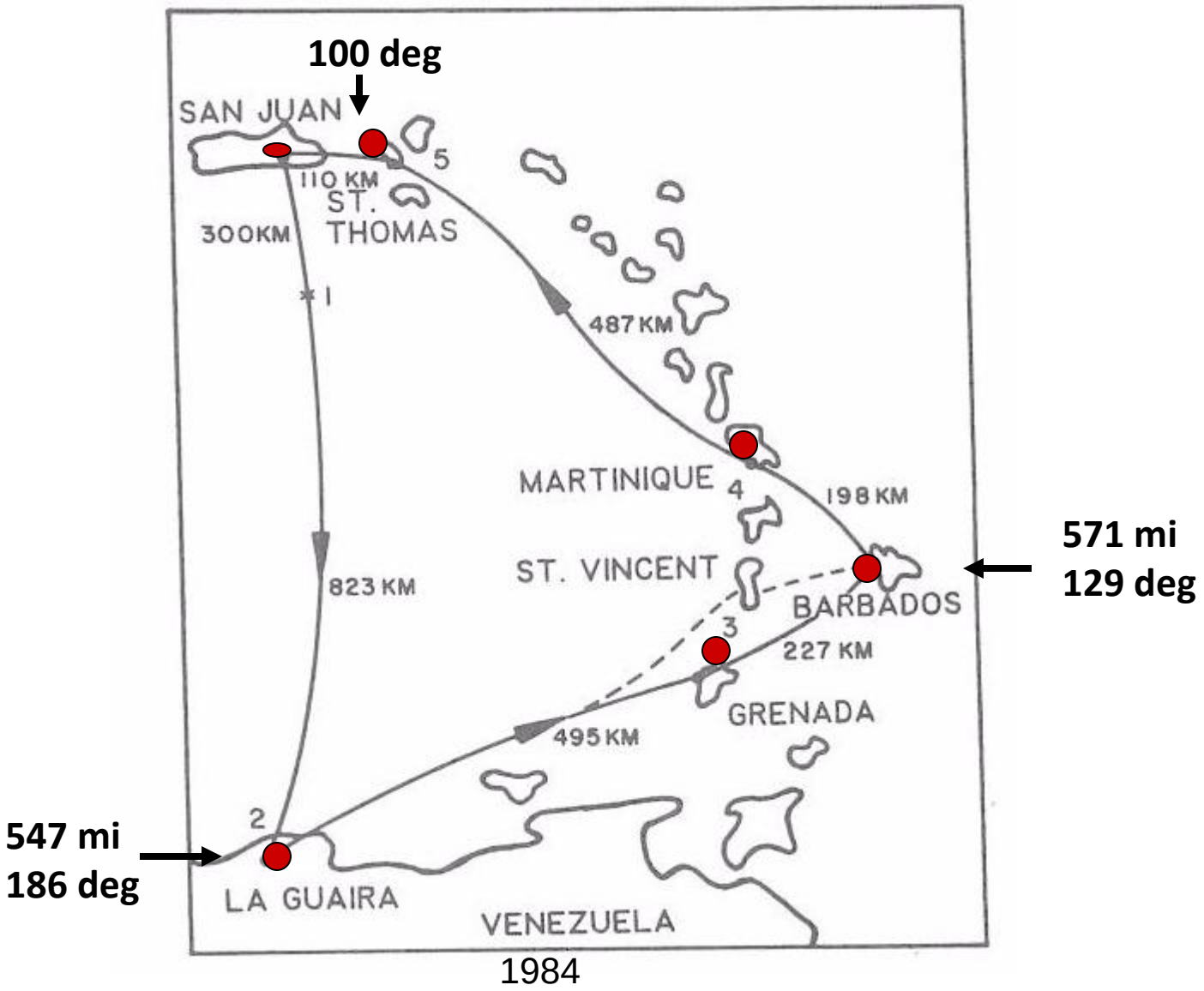
Fig 22

We now expand our measurement program from local measurements to longer and even longer paths.

Ship board measurements around the Caribbean and finally the long path from Arecibo to State College and other paths.

Fig 23

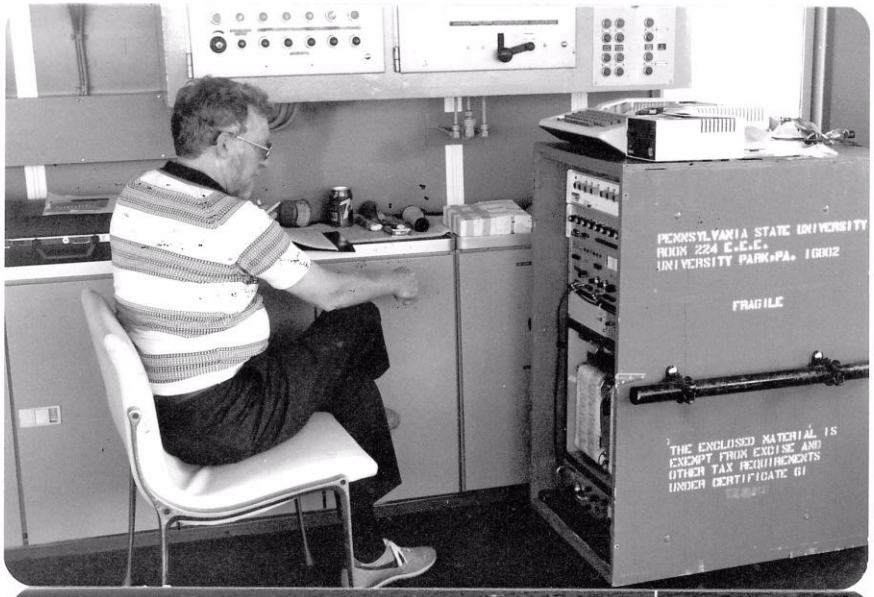
Map of route during shipboard experiments



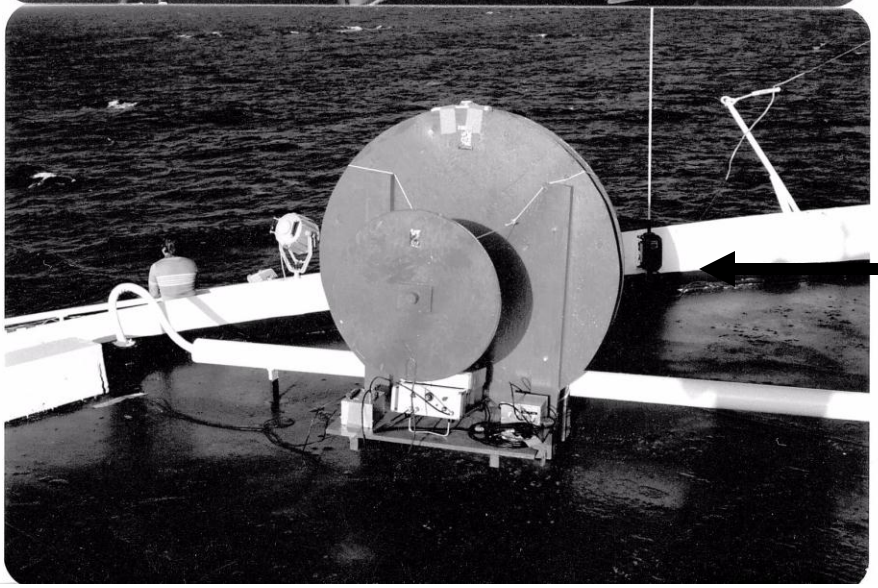
1984

Fig 24

ELF/VLF measurements aboard ship in the Caribbean



A more compact design of the VLF detectors



The VLF loop on the deck

Fig 25

Digital transmission using PSK from the ionospheric antenna, Arecibo to PSU in 1984

1011 1011 1011 1011 1011……

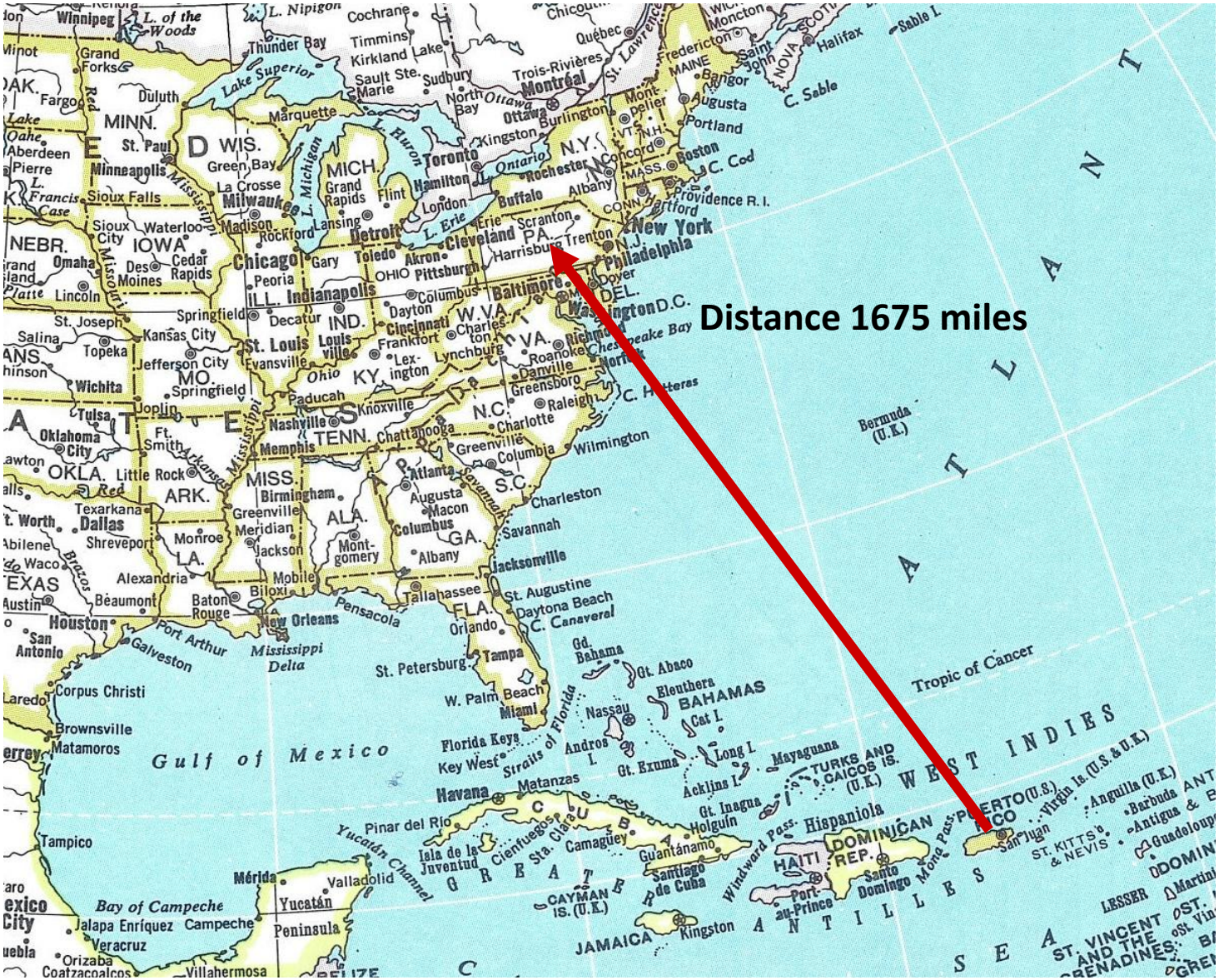


Fig 26

We never talked to submarines!

Cross correlation showing the first two bits are 180 degrees out and the next bits are in phase, for 1011 message.

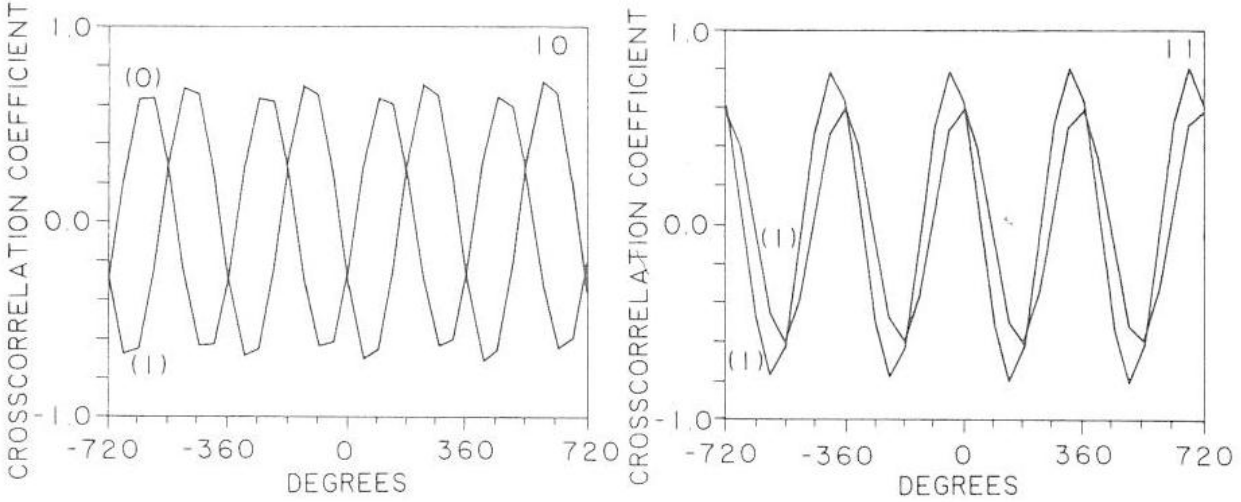


Fig. 10. Cross correlation of synchronous averaged data for a four-bit sequence 1011 with a standard phase reference. Plot on the left shows first two bits and right plot shows last two bits, 1838 Hz, January 20, 1984, 1530-1630 UT.

Fig 27

Alexander von Humboldt observed that there are three stages in scientific discovery: first people deny that it is true; then they deny that it is important; finally they credit the wrong person.
—cited in *A Short History of Nearly Everything*, by Bill Bryson, p. 421

Fig 28

HIPAS* heating facility comes on line in Fairbanks , Alaska.

Here is an opportunity to explore using the PEJ current system as the current source to generate ELF/VLF.

A contract with ONR gives PSU the responsibility to evaluate the generation capabilities from the PEJ.

*High Power Auroral Simulation

Fig 29

Map showing the location of the mobile receiver

Fig 30

1989

Exploring the EEJ using the 50 MHz facility

The Jicamarca Transmitter

- A 50 MHz Incoherent Scatter Radar (ISR)
- Located under the equatorial electrojet
- Approximately 2 MW of RF output power
- Maximum duty factor of 6%
- Not a good ionospheric heater, but the only existing facility that might produce detectable results

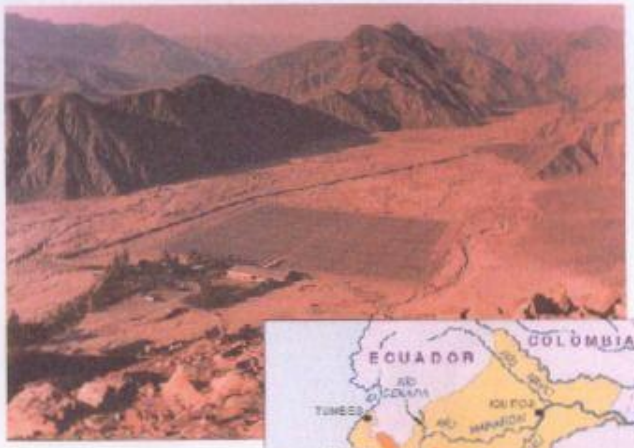


Fig 31

HAARP*

The ONR/AFRL funds an even larger heating facility located between Fairbanks and Anchorage.

PSU plays a role with APTI in the design of this array

* High Frequency Active Auroral Research Program

Fig 32

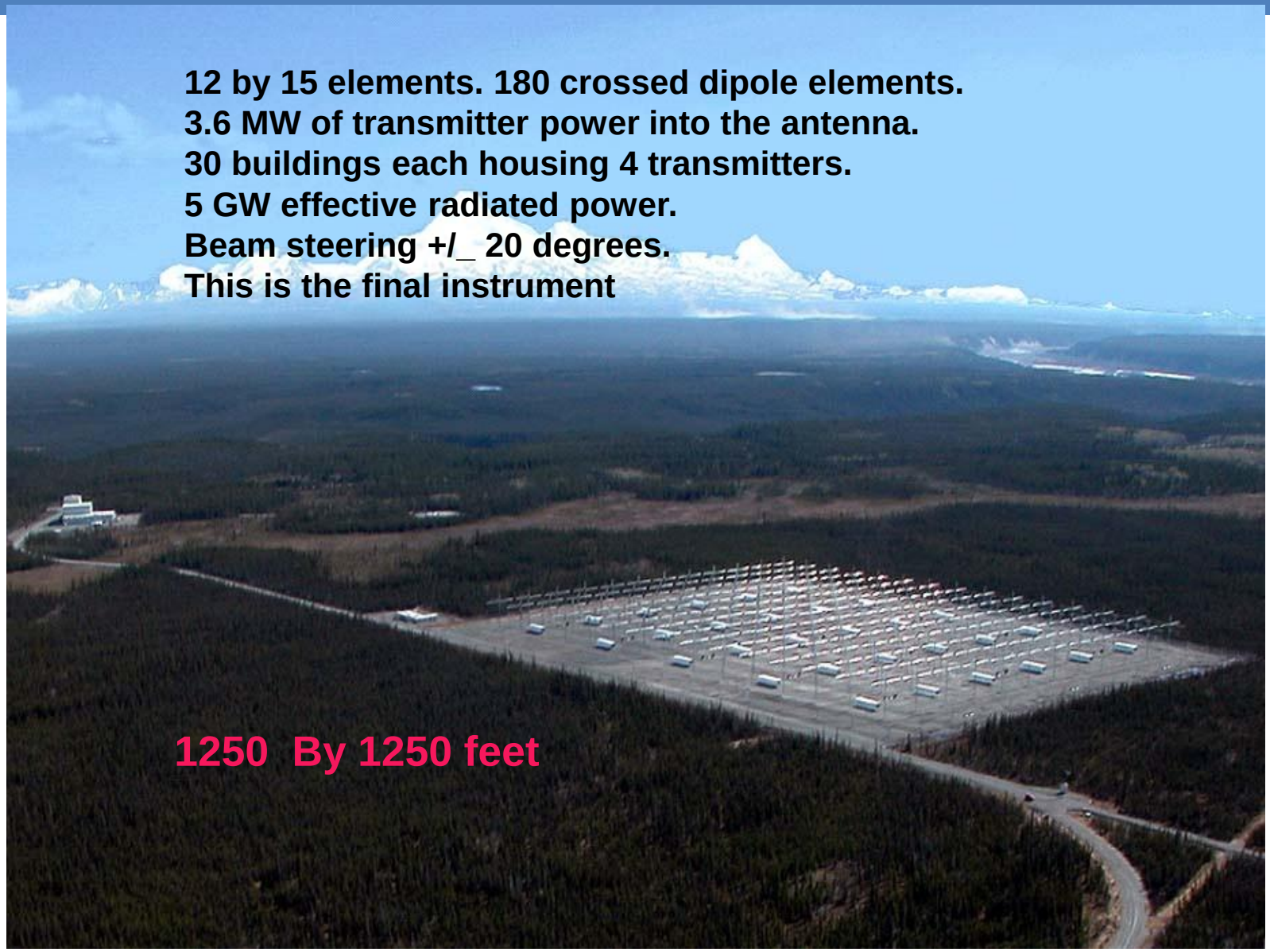
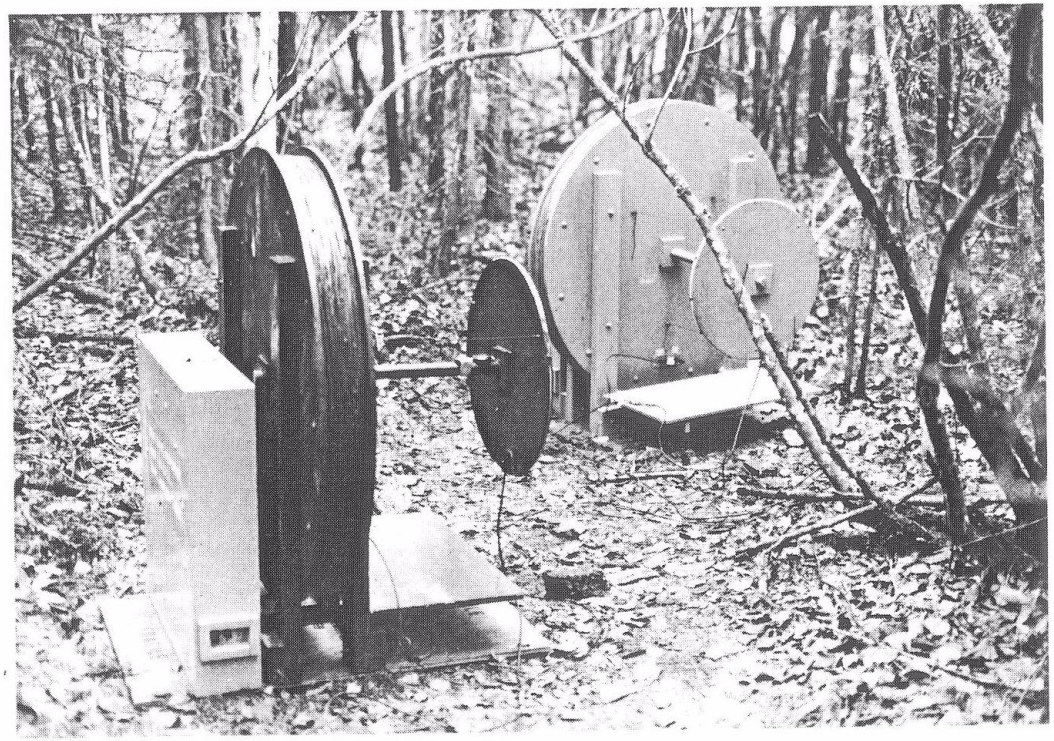

12 by 15 elements. 180 crossed dipole elements.
3.6 MW of transmitter power into the antenna.
30 buildings each housing 4 transmitters.
5 GW effective radiated power.
Beam steering +/_ 20 degrees.
This is the final instrument
1250 By 1250 feet

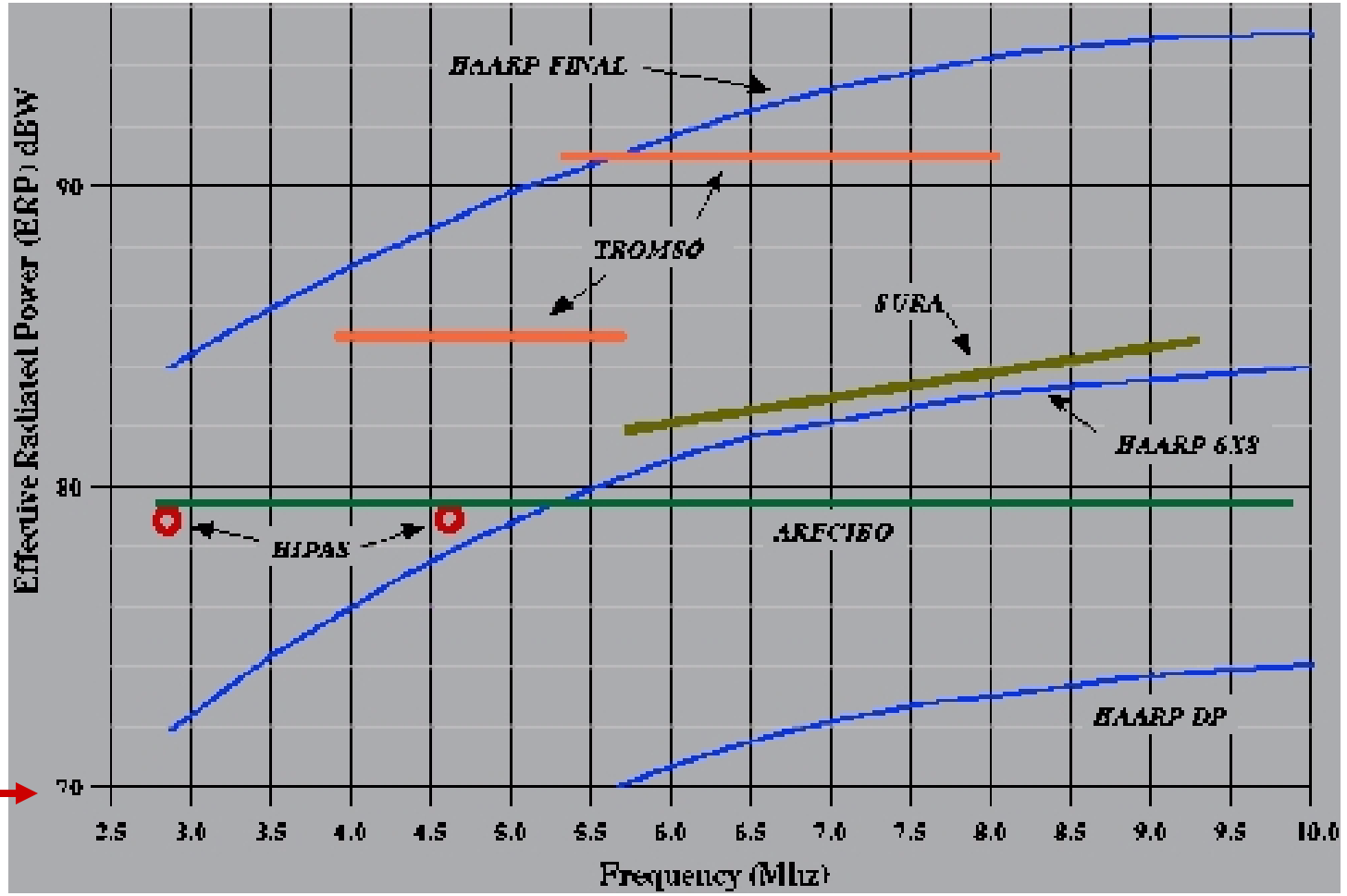
Fig 33



Loop antennas to receive the ELF/VLF signals.
Orthogonal loops for polarization measurement

Fig 34

Comparing the effective radiated powers of the large heater facilities



PSU 1960's

Figure 39

Fig 35